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Assessment of macroinvertebrate community structure in relation to substrate type and water quality using belt transect and principal component analysis

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ABSTRACT

Marine macroinvertebrates are essential organisms that contribute significantly to the structure and function of aquatic ecosystems such as coral reef. This study examined the relationship between substrate types and macroinvertebrate communities in the Sempu Strait, Malang, to understand the ecological interactions within the coral reef ecosystems. Using belt transect and quadrat transect methods, macroinvertebrate species were recorded and analyzed for their diversity, density, and distribution across different substrates, such as hard coral, macroalgae, dead coral, sand, and rubble. The data conducted in 5 stations in Sempu Strait. The findings revealed that hard coral and macroalgae positively influenced macroinvertebrate abundance, whereas dead coral and muddy substrates were associated with lower diversity and density. A total of 706 macroinvertebrates were recorded, belonging to six classes and 16 genera. Among the stations, the Floating House station exhibited the highest coral cover and macroinvertebrate abundance, while the Jetty station had the highest dominance of *Diadema* and the lowest diversity, suggesting a disturbed habitat. The principal component analysis demonstrated significant relationships between substrate types and the abundance of specific macroinvertebrate species. For example, the *Tridacna clam* showed a positive correlation with macroalgae, while *Diadema* was more prevalent on silt and dead coral substrates. The study emphasizes the importance of substrate complexity in supporting macroinvertebrate diversity and highlights the need for maintaining healthy coral reef ecosystems to preserve biodiversity in the Sempu Strait.

Keywords: belt transect, community structure, coral reef, macroinvertebrate, principal component analysis, sempu strait, substrate type, water quality.

INTRODUCTION

Coral reef ecosystems are renowned for their extraordinary biodiversity and ecological significance, supporting about one-third of all marine species. The structural complexity of coral reefs plays a critical role in maintaining invertebrate biodiversity by providing habitat, food sources, and protection from predators (Ferrari et al., 2016; Nelson et al., 2016). The relationship between coral substrate and invertebrate diversity is shaped by reef condition: mosaics of live coral, dead coral with algae, rubble, and sand can reorganize available niches and alter which taxa dominate. This pattern underscores the importance of substrate heterogeneity for maintaining invertebrate communities, as observed in Pahawang Island and Isla Gorgona, where invertebrate assemblages varied with coral cover and rubble prevalence (Rakhmawati et al., 2022; Valencia and Giraldo, 2021). Equally important, water-quality drivers (e.g., temperature, turbidity/light, nutrients, pH, dissolved oxygen) influence both substrate states and faunal responses by affecting coral calcification, algal growth, and the photic environment (Hoegh-Guldberg et al., 2017; Chou, 2016; Storlazzi et al., 2015).

Marine invertebrates – particularly macroinvertebrates (>0.5 mm) – are prominent residents of coastal habitats such as coral reefs (Wulandari et al., 2022; Jacobsen et al., 2007; Lu et al., 2021). They are sensitive to environmental change and cumulative human pressures (habitat conversion, overexploitation, and climate change), so shifts in water quality often translate into measurable changes in community composition, biomass, and ecosystem functions (Bonifácio et al., 2019; Ehrnsten et al., 2020). Several macroinvertebrates (e.g., *Diadema setosum*) also serve as bioindicators of water quality and disturbance (Asante et al., 2023; Uğurlu, 2023), linking substrate condition and hydro-oceanographic variability to detectable changes in benthic assemblages (Duque et al., 2022; Wambua et al., 2021).

At the habitat scale, the structural complexity and texture of the bottom – across seagrasses, live corals, algae, dead coral, sand and rubble – mediate settlement, shelter, and foraging opportunities for macroinvertebrates (Mahilac et al. 2023; Sahidin et al. 2025). Surface characteristics (smooth vs. rough) can facilitate or inhibit attachment and colonization, steering community structure (Bhandari et al. 2019; Bae et al. 2022). Comparative work on artificial versus natural substrates shows consistent differences in colonization pathways, reinforcing how substrate type and microtopography filter benthic taxa (de Camargo et al., 2019). In Sempu Strait, prior studies already link hydro-oceanographic parameters to coral cover and competitive interactions with macroalgae (Isdianto et al., 2022; Isdianto et al., 2023a), indicating a setting where substrate and water quality co-determine macroinvertebrate patterns.

Sempu Strait encompasses the waters around the Sempu Island Nature Reserve (~980 ha) in southern Malang Regency (Luthfi and Jauhari, 2014). Once known for extensive coral reefs, the area has experienced declines associated with local exploitation and coastal modification (Wibawa and Luthfi, 2017). Reclamation and related sediment inputs have altered water clarity and substrate composition, processes that are known to constrain coral cover and restructure macroinvertebrate communities (Chou, 2016; Storlazzi et al., 2015; Limmon and Marasabessy, 2019). Recent monitoring using Reef Check recorded high *Diadema* abundance (Isdianto et al., 2023b), consistent with disturbed or simplified habitats where herbivores and opportunists can dominate.

MATERIALS AND METHODS

Study area

The research was conducted in August 2023, November 2023, and May 2024 in Sempu Strait Waters, Sendang Biru Hamlet, Tambakrejo Village, Sumbermanjing Wetan District, Malang. The selection of five stations (Figure 1) was done by purposive sampling, the selection of stations was based on the representativeness factor of regional characteristics with a minimum of three stations (Giyanto et al., 2014). The selection of the five stations was based on certain reasons. The coordinates of each research station can be seen in Table 1.

Sampling

Macroinvertebrate data were obtained using visual census with the belt transect method (Figure 2). The belt transect method used had dimensions of 1 × 100 m (width × length), with the width divided into two parts, 2.5 m on each side of the transect line (English et al., 1998). Macroinvertebrate specimens found were then morphologically analyzed for each specimen using the reference book *Guide to Monitoring Megabenthos, 2nd Edition* (Arbi and Sihaloho, 2017) and the official website *World Register of Marine Species*: http://www.marinespecies.org/index.php.

Substrate data was collected using the quadrat transect method and underwater photo transect (UPT) (Figure 3) by taking underwater photographs using either a digital underwater camera or a regular digital camera enclosed in a waterproof housing to prevent seawater leakage. Ten transects measuring 1 × 1 m were placed at each station at a depth of 2–6 m, with a distance of approximately 10 m between transects.

The oceanographic data on the physical-chemical properties of the water, including

Table 1. Description of stations

Station	Coordinates (Long, Lat)	Description
Watu Meja	112.6973, -8.42928	Located at the eastern tip of Sempu Strait, characterized by a large rock resembling a table, hence named "Watu Meja" (meaning "rock table" in Javanese).
Waru-Waru	112.6932, -8.43009	Known for its white sandy beach, it is a popular tourist destination. However, tourism activities lead to waste accumulation on land and in the sea, impacting coral reefs.
Banyu Tawar	112.6897, -8.43312	A location known for its freshwater influx, often used as a docking site for fishing vessels.
Jetty	112.6842, -8.4338	The area is impacted by anthropogenic activities, such as waste disposal, shipbuilding, and fuel spills, which affect marine life and coral reefs.
Floating House	112.68, -8.43679	Located at the western tip of Sempu Strait, near a port. This station is frequently affected by waste deposits from the port, impacting the surrounding coastal area.

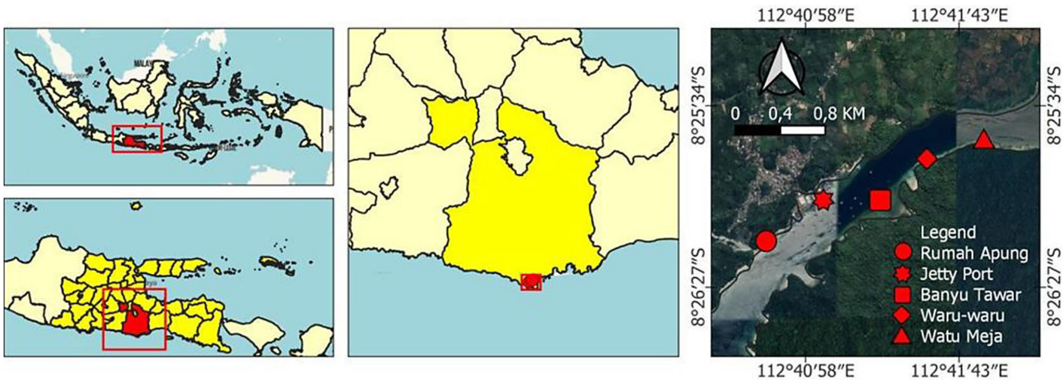


Figure 1. Research location

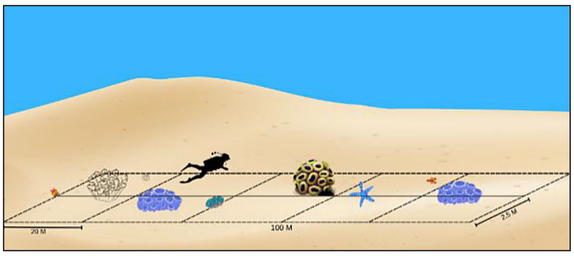


Figure 2. Belt transect method

temperature, salinity, DO, and pH, were collected in-situ using the AAQ 1183 sonde, with three repetitions. Measurements were taken at depths of 0, 5, and 10 meters at five station points. For nitrate and phosphate, water samples were collected in polyethylene bottles and later analyzed in the laboratory using the spectrophotometer method. Current speed was measured in-situ using a current meter with the Eulerian method. Sedimentation rate was measured using a sediment trap installed on the seafloor. Water clarity was calculated using a Secchi disk, by averaging the depth at which the disk was first visible and the depth at which it was no longer visible.

Data analysis

Density

The density of macroinvertebrates is influenced by several chemical and physical factors of a water body, including temperature, currents, pH, and river runoff carrying chemicals from the land. Data analysis used to calculate the density and distribution patterns of invertebrates is based on the following formulas:

$$K_i = \frac{N_i}{A} \tag{1}$$

where: K_i – species density (ind/m^2), N_i – total individu of species-*i*, A – total observation area.

Diversity

Species diversity in a community refers to the variety of organisms that make up the community. Low macroinvertebrate diversity indicates poor water quality or pollution. The diversity of invertebrates is calculated using the Shannon-Wiener index (Krebs, 2014)

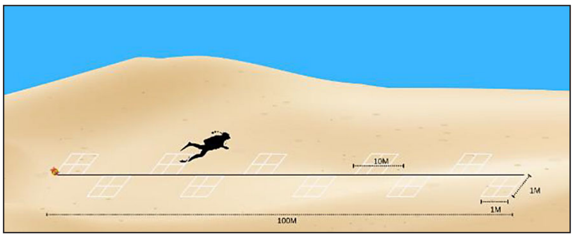


Figure 3. Quadrant transect

$$H' = -\sum_{i=s}^{s} pi\ ln\ pi \quad (2)$$

where: $Pi = \frac{ni}{N}$, n_i – total individu of species-*i*,
s – total of individu observed.

Evenness

The evenness index aims to determine the distribution patterns of biota and assess the extent of similarity in the distribution of individual counts across different types of macroinvertebrates (Krebs, 2014):

$$E = \frac{H'}{H\ max} \quad (3)$$

where: *E* – evenness index, *H'* – diversity index,
Hmax – maximum of diversity index.

Dominance

The dominance value of invertebrates is calculated using Simpson's dominance index equation. The dominance index is a parameter that indicates the degree of species dominance concentration within a community (Kumar and Mina, 2014).

$$D = \sum_{i=1}^{n} pi^2 \quad (4)$$

where: *D* – Simpson's dominance index,
Pi – ni/N, *Ni* – number of individuals of a species, N – total number of individuals of all species.

Coral cover

Substrate conditions are assessed by comparing the total length of each category with the transect length. This coverage analysis is performed using CPCe software (Table 2) (Giyanto et al., 2014):

$$Coral\ cover = \frac{(total\ point\ of\ categories\ observed)}{(total\ of\ random\ points)} \times 100\% \quad (5)$$

Statistical analysis (PCA)

The calculation to determine the relationship between macroinvertebrate abundance and substrate type utilizes the principal component analysis (PCA) method with XL-STAT software. PCA serves as a powerful statistical technique for reducing the dimensionality of multivariate data while preserving its essential features. The primary goal of PCA is to transform a large set of interrelated variables into a smaller set of uncorrelated variables, known as principal components, which can explain most of the variability within the data. This transformation not only simplifies the dataset but also enhances the interpretability of the underlying patterns (Adugna et al., 2023; Omprakash and Gokila, 2018). The use of PCA in analyzing macroinvertebrate assemblages has been documented in various studies, indicating its effectiveness in elucidating ecological patterns. For instance, Retnaningdyah et al. employed PCA to establish models linking ecological indices, such as species diversity, with water quality parameters, affirming that PCA can reveal significant relationships between macroinvertebrate communities and environmental conditions (Retnaningdyah et al., 2023).

RESULTS AND DISCUSSION

Water parameters

Across the five stations (Table 3), seawater temperature was relatively cool (25.41–25.85 °C),

Table 2. Community sructure categories

H'	Criteria	E	Criteria	C	Criteria
H' < 1	Low	0<E<0.4	Depressed	0<C<0.5	Low
1<H'<3	Moderate	0.4<E<0.6	Unstable	0.5<C<0.75	Moderate
H'>3	High	0.6<E<1	Stable	0.75<C<1.0	High

salinity was stable (34.32–34.35 ppt), pH ranged from 7.43 to 7.97, dissolved oxygen (DO) from 6.68 to 6.73 mg L^{-1}, water clarity (Secchi depth) from 1.95 to 5.70 m, sedimentation from 74.23 to 179.82 mg cm^{-2} day^{-1}, nitrate from 0.11 to 1.75 mg L^{-1}, phosphate from 0.03 to 0.15 mg L^{-1}, and current speed from 0.17 to 0.77 m s^{-1}. These observations frame the physico-chemical context for interpreting benthic and macroinvertebrate patterns in Sempu Strait.

The average water temperature across five stations was consistent, ranging from 25.41–25.85 °C, which is not suitable for coral health, meanwhile macroinvertebrate like gastropoda and Bivalvia found in 29–30 °C (Mawardi et al., 2023). Salinity levels ranged from 34.32–34.35 ppt, slightly above normal, but still supports coral growth. Meanwhile, macroinvertebrates have various tolerances. For example, the *Diadema* sea urchin can thrive at salinities of 30–32 ppt (Dewiyanti et al., 2021), while gastropods and bivalves can be found within a salinity range of 25–32 ppt, particularly in coastal areas near mangrove ecosystems (Mawardi et al., 2023). Changes in temperature and salinity impact the distribution and abundance of macroinvertebrates, with higher temperatures leading to reduced body size, as observed in bivalves and brachiopods during the TOAE (Toarcian Oceanic Anoxic Event) (Piazza et al., 2020). Fluctuations in salinity also affect species abundance, with macroinvertebrates in rocky substrates being more diverse and resilient compared to those in muddy and sandy substrates (Sahidin et al., 2025). Temperature and salinity variations can alter macroinvertebrate community structure, with species more tolerant to environmental changes becoming dominant. As a result, more sensitive species decline in abundance or become extinct, influencing species diversity within ecosystems (Stortini et al., 2020).

Regionally, comparable work in Inner Ambon Bay, Indonesia shows how chronic sediment inputs interact with local thermal regimes to affect coral condition (Limmon and Marasabessy, 2019). In the Caribbean, watershed syntheses link warming beyond local baselines with bleaching and community shifts, often coinciding with land-derived sediment delivery (Rogers and Ramos-Scharrón, 2022). From the Gulf of Mannar, India, observations on coral spat recruitment further illustrate the sensitivity of early life stages to seasonal thermal windows on tropical reefs (Marimuthu et al., 2019). At a broader Indonesian scale, post-uplift hydrographic changes documented for Nias–Simeulue highlight how regional processes can alter nearshore water properties and reef habitat conditions (Sosdian et al., 2024).

The measured pH values ranged from 7.43–7.97, which is optimal for aquatic life, particularly for organisms that rely on carbonate to form their exoskeletons, such as corals and shellfish. A decrease in ocean pH due to increased CO_2 absorption can lead to difficulties in calcification and potential dissolution of existing calcium carbonate structures (Hoegh-Guldberg et al., 2017; Prahalad

Table 3. Water parameters result

Parameters	Station					Threshold
	WM	WW	BT	JT	RA	
Temperature (°C)	25.54	25.41	25.85	25.78	25.44	28–30[a]
Salinity (ppt)	34.32	34.32	34.32	34.32	34.35	33–34[a]
pH	7.93	7.89	7.97	7.47	7.43	7–8.5[a]
DO (mg/L)	6.72	6.73	6.68	6.69	6.73	>5[a]
Brightness (m)	4.61	4.33	4.56	1.95	5.70	>5[a]
Sedimentation (mg/cm^2/day)	74.23	93.23	110.24	179.82	84.31	1–10: slight-moderate[b] 10–50: moderate-severe >50: severe-catastrophic
Nitrate (mg/L)	1.07	1.29	0.11	1.75	0.92	0.06[a]
Phosphate (mg/L)	0.03	0.07	0.05	0.15	0.05	0.015[a]
Current (m/s)	0.77	0.63	0.43	0.17	0.33	Slow: 0-0.25 m/s[c] Moderate: 0.25–0.50 m/s Fast: 0.50–1 m/s Very fast: >100 m/s

Note: WM: Watu Meja; WW: Waru-Waru; BT: Banyu Tawar; JT: Jetty; RA: Floating House.
Source: Government Regulation No. 22, 2021[a] for coral; Pastorok and Bilyard 1985[b]; Ramlah et al. 2015[c].

et al., 2020). Meanwhile, issolved oxygen (DO) levels in the water ranged from 6.68 mg/L to 6.73 mg/L, which is also within the optimal range. Fluctuations in dissolved oxygen are crucial for macroinvertebrates, as low oxygen levels can stress species and affect their survival and functions, with stable DO being essential for sustaining their ecological roles, especially in vulnerable habitats like seagrasses and mangroves (Asante et al., 2023).

In an urbanized tropical setting such as Singapore, long-term coastal modification has been associated with altered water-quality baselines, including variability in carbonate chemistry relevant to coral calcification (Chou, 2016). Along the Kenyan coast in the Western Indian Ocean, field studies show that water-quality stressors – including episodes of low DO – restructure reef-associated microbiomes with implications for benthic organisms (Wambua et al., 2021). These comparative cases underscore that even modest departures from typical pH and DO conditions can cascade through coral-associated communities.

For nutrient parameters, nitrate levels ranged from 0.11–1.75 mg/L, while phosphate levels ranged from 0.03–0.15 mg/L, exceeding the established limits. The enrichment of nutrient components leads to a decrease in coral resistance to disease induction by viruses and pathogenic bacteria (Zhao et al., 2021). Meanwhile, the effect of high concentrations of nitrates and phosphates on macroinvertebrate species, known negatively affecting the species richness and biomass, with some species showing tolerance to nutrient-enriched environments, highlighting the impact of eutrophication on estuarine ecosystems (Duque et al., 2022).

Experimental and field-informed work from Okinawa, Japan demonstrates that phosphate bound to calcareous sediments can be released to seawater and inhibit skeletal development in juvenile corals (Iijima et al., 2021). Laboratory and mesocosm evidence from Florida/USA shows additive negative effects of fine anthropogenic sediment and warming on coral recruits (Fourney and Figueiredo, 2017), with recent physiology pointing to transcriptomic 'tipping points' under high sediment loads in reef-building corals (Lock et al., 2024). Optical measurements from USGS further indicate that fine, dark terrigenous particles disproportionately attenuate light, compounding photic stress on zooxanthellate corals (Storlazzi et al., 2015). Consistent patterns at ecosystem scale are reported in the Caribbean, where catchment-to-reef sediment delivery is associated with reduced coral cover and biodiversity (Rogers and Ramos-Scharrón, 2022), and larval performance of a threatened Caribbean coral declines with increasing suspended-sediment dose (Serrano et al., 2024). Similar sediment- and nutrient-linked pressures on reefs have been documented in Indonesia (Limmon and Marasabessy, 2019), while global syntheses emphasize the role of rising ocean temperatures acting together with local stressors to elevate colony-level mortality (NM et al., 2024).

The measured water clarity ranged from 1.95–5.70 meters, with the lowest value found at the Jetty Station (1.95 meters), corresponding to the shallow harbor location. Sedimentation levels ranged from 74.23–179.82 mg/cm²/day, which is categorized as high (Pastorok and Bilyard, 1985). High sedimentation and turbidity reduce light availability for coral photosynthesis, leading to decreased coral health, as it hinders photosynthesis and increases the energy costs required for sediment removal from coral surfaces. This results in oxidative stress, increased apoptosis, and impaired metabolic functions, ultimately affecting coral growth, reproduction, and survival (Asmawi et al., 2020; Lock et al., 2024).

Comparative optical work shows that small changes in particle composition can strongly reduce underwater light fields, meaning that sites with elevated turbidity will experience lowered photosynthetic potential even at similar depths (Storlazzi et al., 2015). Such clarity constraints align with experimental evidence from Florida on reduced survival and growth of coral recruits under chronic fine-sediment exposure (Fourney and Figueiredo, 2017).

Lastly, current speeds varied between 0.17–0.77 m/s, categorized as slow to fast. Current speed plays a crucial role in coral reef health by regulating both phytoplankton distribution and sediment dynamics. It transports nutrient-rich water, promoting phytoplankton abundance and diversity, which serves as a primary food source for macroinvertebrates (Chi et al., 2023; Zhou et al., 2024). Additionally, variations in current speeds affect sediment capture and turbidity, influencing benthic habitat conditions around corals (Mienis et al., 2019).

Hydrodynamics reported for nearshore fringing reefs in Culebra Island, Puerto Rico illustrate how along-shore currents and wave events mediate sediment resuspension and deposition, thereby modulating light availability and benthic stability (Otaño-Cruz et al., 2017). In combination with local nutrient sources, these current regimes influence phytoplankton supply and sediment transport, with downstream effects on reef food webs and habitat quality.

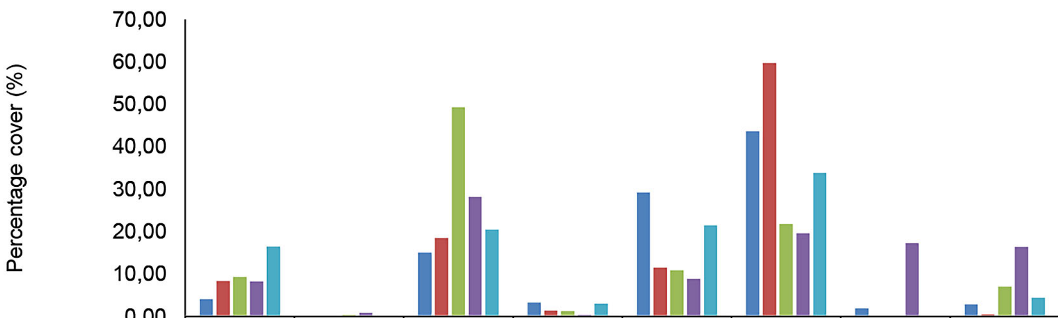
Substrate coverage

Based on the result of substrate monitoring (Figure 4), the station with the highest percentage of live coral cover was Floating House, with a value of 16.47%, while the station with the lowest percentage of live coral cover was Watu Meja, with a value of 4.10%. The live coral cover values for the other stations were Waru-Waru at 8.33%, Banyu Tawar at 9.28%, and Jetty at 8.28%. According to the Decree of the State Minister for the Environment No. 4 of 2001, all five research stations fall into the ”damaged” category. A previous study conducted in 2018 reported that the percentage of live coral cover in Selat Sempu ranged from 6.94–42.4%, indicating conditions from damaged to moderate (Luthfi et al., 2018). This suggests that coral cover in the waters of Selat Sempu has declined over the six-year period.

At station Floating House, the dominant substrate is live coral (hard coral), with a coverage value of 16.47%. This indicates a relatively better coral reef ecosystem compared to other stations, with more stable substrates supporting higher species diversity. Live corals play an essential role in providing habitat stability and supporting biodiversity. Moreover when corals die, invertebrate communities experience significant shifts, with opportunistic species colonizing the substrate, followed by a decline in species richness as the coral structure deteriorates (Hoegh-Guldberg et al., 2017; Rhoades et al., 2023).

At station Waru-Waru, the dominant substrates are sand, with additional macroalgae and rubble (rock fragments). Sand as the primary substrate tends to provide a more open habitat, which is less ideal for species that require hard substrates. However, the presence of macroalgae and rubble adds some variation to the habitat, though it is not as abundant as in stations with live coral. Dominance of sand can affect the abundance of macroinvertebrates, as it does not offer adequate shelter, limiting species diversity. But the presence of macroalgae can affect the coral health. Similarly to previous research, the competition between corals and macroalgae is prevalent in various marine habitats, where conditions favor rapid algal growth, thus suppressing coral recovery (Isdianto et al., 2023a).

At station Banyu Tawar, the dominant substrate is dead coral with algae (dead coral with algae – DCA), which indicates coral reef degradation. This condition promotes the growth of macroalgae, as the substrate provides suitable conditions for their colonization. The competition for space between corals and macroalgae is heightened, with macroalgae often outcompeting corals due to their rapid growth on degraded coral skeletons (Isdianto et al., 2023a). As macroalgae grow, they further exacerbate coral loss by limiting space for coral recovery, leading to a feedback loop of substrate degradation and diminishing biodiversity. This result aligned with previous study stated that Banyu Tawar has the highest turf



	HC	DC	DCA	MA	R	S	SI	RK
Watu Meja	4,10	0,00	15,10	3,26	29,24	43,61	1,87	2,82
Waru-waru	8,33	0,00	18,53	1,33	11,53	59,73	0,00	0,53
Banyu Tawar	9,28	0,40	49,31	1,27	10,87	21,81	0,00	7,07
Jetty	8,28	0,87	28,15	0,40	8,89	19,64	17,24	16,37
Rumah Apung	16,47	0,00	20,53	3,00	21,47	33,87	0,00	4,40

Figure 4. Average of substrates coverage in sempu strait

algae cover on the dead coral skeleton among five stations (Isdianto, 2024).

Similar trajectories are reported for nearshore Caribbean reefs where macroalgae occupying dead-coral substrates suppress coral recovery and reorganize benthic guilds – e.g., Culebra Island, Puerto Rico (Otaño-Cruz et al., 2019) – and for the Great Barrier Reef (Australia), where communities colonizing dead-coral framework contribute differently to reef calcification compared with live-coral zones (Orte et al., 2021). Recent mass-bleaching observations on Magnetic Island, Great Barrier Reef (Australia) further underscore how disturbance events accelerate substrate-level degradation (Borghi et al., 2025).

At station Watu Meja, the dominant substrates consist of sand and rubble. This substrate type indicates a harder and more open habitat, which often provides less shelter for species that require more stable and protected substrates. The higher current speed at this station influences sediment distribution and reduces macroinvertebrate abundance, as strong currents can move sediment away from the location and alter substrate condition (Mienis et al., 2019). Stations dominated by sand and rubble mirror habitat simplification documented in Gazi Bay (Kenya), where reduced complexity limits species richness and shifts benthic guilds (Ditzel et al., 2022).

At station Jetty, the dominant substrates are silt, dead coral, and rock. High sedimentation in this area creates substrates that are less ideal for many species that require stable conditions such as live coral. The dominance of silt indicates high sedimentation in the area, which can obstruct coral photosynthesis and affect habitat quality. Human activities, such as port operations, contribute to increased sedimentation and substrate degradation, influencing species diversity (McLeod et al., 2021). In conclusion, the substrate is one of the important factors that influences the distribution of species and community structure besides other water quality parameters (Mahilac et al., 2023).

Comparable sediment-linked constraints on coral growth and benthic diversity are reported from the South China Sea – across multi-site surveys spanning nearshore and offshore reefs (Liao et al., 2021) – and from Indonesian estuarine settings such as the Kawal River estuary, Bintan Island (Riau Islands, Indonesia), where elevated sedimentation coincides with coral disease prevalence (Putra et al., 2023). At broader scales, catchment condition strongly mediates reef recovery potential (Suárez-Castro et al., 2021), while local stressors can heighten disease risks observed in Guam (Micronesia) (Greene et al., 2020).

Community structure profile of macroinvertebrates found in sempu strait

Based on the data from the different stations in Sempu Strait, the analysis of density, diversity, evenness, and dominance provides insights into the macroinvertebrate community structure across the reef ecosystems (Table 4).

Station Jetty exhibited the highest macroinvertebrate density (0.255 ind/m^2), which indicates a relatively higher concentration of individuals at this station, despite its lower diversity index, which explained the higher number of *Diadema* sea uchins in this area (0.209 ind/m^2). This suggests that, although more individuals are present, the species diversity is not as rich. In contrast, station Banyu Tawar had the lowest density (0.034 ind/m^2). Comparable urchin-dominated states have been documented on nearshore reefs of Culebra Island, Puerto Rico (NE Caribbean) where changes in land use and oceanographic conditions reshaped benthic communities (Otaño-Cruz et al., 2019). Experimental work in the Caribbean shows that Diadema antillarum herbivory can strongly suppress algal cover and restructure benthic assemblages (Manuel et al., 2021), while observations from the South Aegean Sea, Greece (eastern Mediterranean) highlight how high Diadema setosum abundance aligns with simplified habitats and low evenness (Vafidis et al., 2021). Further biomonitoring in İskenderun Bay, eastern Mediterranean, Türkiye corroborates the use of Diadema as a stress bioindicator in anthropogenically impacted coasts (Uğurlu, 2023).

The diversity of macroinvertebrates, as measured by the Shannon-Wiener index (H'), was highest at station Banyu Tawar (1.846), indicating a more diverse community structure. This higher diversity can be attributed to the presence of varied substrate types, including both live and dead coral, which provide ecological niches for a wider range of species. On the other hand, station Jetty had the lowest diversity (0.505), which could be due to the dominance of certain species, such as *Diadema* and *Tripneustes*, that limit the overall richness of the invertebrate community. This aligns with previous studies, where the Jetty's diversity was recorded

Table 4. Macroinvertebrate community structure

Station	Density (ind/m²)	Diversity (H')		Evenness (E)		Dominance (C)	
		Value	Category	Value	Category	Value	Category
Jetty	0.255	0.505	Low	0.172	Depressed	0.682	Medium
Floating House	0.062	0.781	Low	1.126	Stable	0.463	Low
Banyu Tawar	0.034	1.846	Medium	1.03	Stable	0.165	Low
Watu Meja	0.060	1.713	Medium	1.064	Stable	0.225	Low
Waru-Waru	0.060	1.311	Medium	1.193	Stable	0.243	Low

as low, between 0.08 and 0.26 over four observations (Isdianto et al., 2023b).

The evenness of species distribution, as indicated by the evenness index (E), varied significantly between the stations. Station Floating House showed a more stable evenness value (1.126), suggesting a more evenly distributed community of species. In contrast, station Jetty had a much lower evenness value (0.172), indicating that a few dominant species, such as *Diadema*, skew the distribution, resulting in a less balanced community structure. This is consistent with earlier findings at the Jetty, where the evenness index was between 0.04 and 0.12, indicating an uneven distribution of species, with some species dominating the ecosystem (Isdianto et al., 2023b). This suggests that the conditions at this station are more stressed, likely a result of human-induced pressures and environmental degradation at the station. Consistent patterns are observed in global reef datasets where greater structural complexity is associated with more even distributions of benthic taxa (Ferrari et al., 2016), whereas simplified or disturbed states tend to concentrate abundance into a few tolerant species, reducing evenness (Nelson et al., 2016).

In terms of dominance, station Jetty again showed the highest dominance index (0.682), driven by the overwhelming abundance of *Diadema*, making it the most dominant species at this station. The higher dominance at Station Jetty reflects a community structure that is largely dominated by a single species, which reduces overall community diversity. Conversely, station Waru-Waru and station Banyu Tawar exhibited much lower dominance values (0.243 to 0.225), indicating a more evenly distributed species composition and less influence from any single species. This is in line with previous studies, which found dominance values ranging from 0.89–0.95 over four observations temporally (Isdianto et al., 2023b). Analogous dominance by a few taxa under disturbance has been noted on Culebra Island, Puerto Rico (Caribbean) amid shifts in sedimentation dynamics (Otaño-Cruz et al., 2019), and disease-linked community instability reported from Guam, Micronesia underscores how local stressors can amplify benthic homogenization (Greene et al., 2020).

Overall, station Banyu Tawar stands out for its more balanced macroinvertebrate community, likely due to its more diverse substrates and the presence of both live and dead corals, which provide more habitat opportunities. Station Jetty, however, demonstrates a skewed community structure with lower diversity, high dominance, and depressed evenness, suggesting the impact of habitat degradation and human activities. These findings underscore the critical role of substrate quality and habitat complexity in shaping macroinvertebrate populations, as well as the importance of maintaining healthy reef ecosystems for biodiversity conservation.

Regional and international case studies reinforce this substrate–community coupling: rubble/low-relief habitats in Gazi Bay, Kenya (Western Indian Ocean) support altered urchin and fish guilds compared with more complex reefs (Ditzel et al., 2022), while gradients in coral cover at Isla Gorgona, Colombia and observations from Pahawang Island, Lampung, Indonesia show cryptic and sessile invertebrates tracking substrate heterogeneity (Rakhmawati et al., 2022; Valencia and Giraldo, 2021). For deposit-feeding macroinvertebrates, targeted studies in Gulf of Mannar and Palk Bay, India and Duroa Island, Tual City, Maluku, Indonesia document habitat-linked peaks in sea cucumber occurrence where organic-rich sediments and reef structures co-occur (Asha et al., 2019; Kalidi et al., 2023).

Based on the results found, the overall macroinvertebrate results were 706 individuals with details at Watu Meja station as many as 90 individuals, Waru-Waru 90 individuals, Banyu Tawar

51 individuals, Jetty 382 individuals and Floating House as many as 93 individuals. Macroinvertebrates were found which were divided into 6 classes and 16 genera which can be seen in Table 5. The documentation of macroinveretebrate shown in Figure 5.

Relationship of macroinvertebrate abundance with substrate type

The association of macroinvertebrates with substrate types was analyzed using principal component analysis (PCA) (Figure 6) using the abundance value of macroinvertebrate individuals with substrate types. The results conducted at five research stations showed that the maximum information regarding the relationship between observation stations, macroinvertebrate abundance, and substrate types was centered on variance 1 (F1) and variance 2 (F2). The total variance (F1 and F2) represented 68.56% of the total data variation, with variance 1 (F1) having a characteristic root and variance contribution of 45.77%, while variance 2 (F2) had a characteristic root and variance contribution of 22.79%.

Floating House station showing the primary characteristic substrates are macro algae (MA) and sand, with MA being the stronger indicator, as its line is farther from the origin, although the difference is not significant. In contrast, Hard Coral, *Drupella*, and *Echinotrix* substrates show weaker associations across all stations. However, based on the angle of the axes, hard coral and *Drupella* are closely linked to station Floating House, consistent with findings that this station has the highest hard coral cover and the greatest abundance of *Drupella*. Dominant species at this station, including *Trochus*, *Drupella*, and *Tridacna*, show a positive correlation with hard coral substrates. *Trochus* is found exclusively at station Floating House. *Drupella* has a strong relationship with hard coral, as these snails feed on coral polyps. When *Drupella* populations are abundant, they preferentially target corals, causing significant tissue loss and increasing coral vulnerability to diseases (Ulfah et al., 2022; Zhang et al., 2023). Meanwhile, *Tridacna* has a strong and positive association with macro algae, suggesting its abundance increases as the coverage of macro algae increases.

Comparable patterns linking higher hard-coral fractions to richer macroinvertebrate guilds are reported at Isla Gorgona, Eastern Tropical Pacific (Colombia), where cryptic invertebrate richness increases along coral-cover and habitat-complexity gradients (Valencia and Giraldo, 2021), and at Pahawang Island, Lampung (Indonesia), where invertebrate diversity tracks substrate heterogeneity (Rakhmawati et al., 2022). Across

Table 5. Number of macroinvertebrates individuals in Sempu Strait

Class	Genus	Number of invertebrate (ind)					Total
		JT	FH	BT	WM	WW	
Echinoidea	Diadema	313	8	3	0	13	337
	Echinotrix	5	3	1	0	3	12
	Tripneustes	3	0	0	0	1	4
Crinoidea	Comaster	3	2	8	31	37	81
	Holothuria	0	0	3	0	0	3
	Synapta	0	0	2	0	0	2
Asteroidea	Echinaster	0	0	3	25	2	30
	Culcita	0	0	1	1	0	2
Gastropoda	Drupella	33	60	16	9	10	128
	Trochus	0	1	0	0	0	1
	Phyllidiella	0	1	0	6	0	7
	Phyllidia	4	0	0	0	0	4
Bivalvia	Tridacna	0	18	7	9	17	51
Malacostraca	Stenopus	0	0	1	4	4	9
	Trapezia	1	0	1	5	0	7
	Cymo	20	0	5	0	3	28
Total		382	313	93	51	90	90

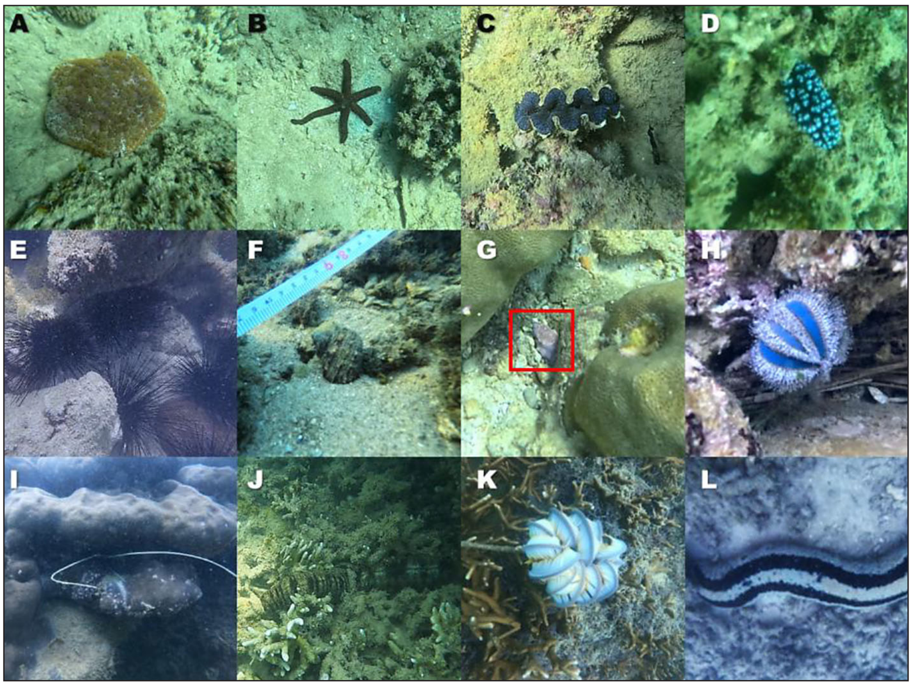


Figure 5. Macroinvertebrates recorded in Sempu Strait. (A) Culcita; (B) Echinaster; (C) Tridacna sp; (D) Phyllidiella; (E) Diadema; (F) Trochus; (G) Drupella; (H) Tripneustes; (I) Stenopus; (J) Synapta; (K) Comaster; (L) Holothuria

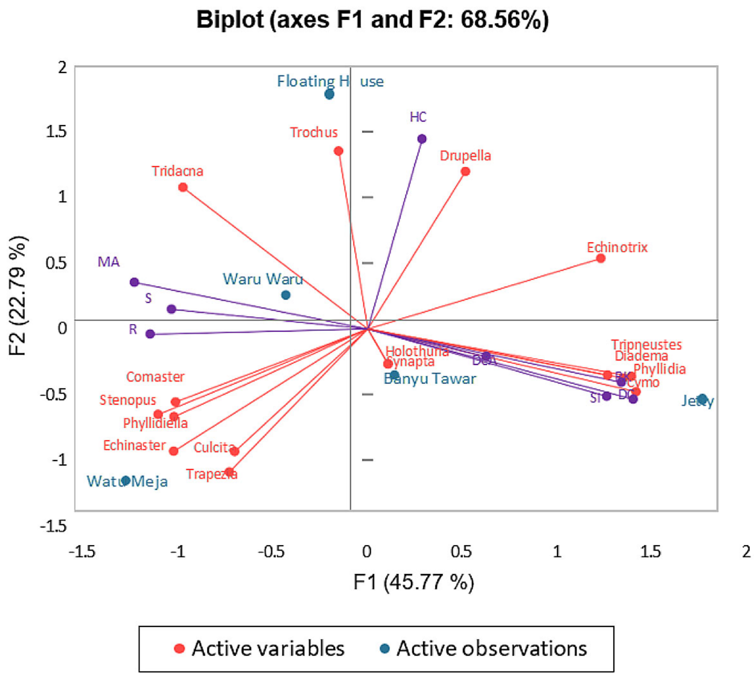


Figure 6. Relationship between macroinvertebrate abundance and substrate type

the Indo-Pacific core range, species-distribution modeling also identifies habitat windows for Tridacna maxima consistent with well-lit substrates used by symbiotic clams (Liu et al., 2024).

Both station Waru-Waru and station Watu Meja have primary characteristic substrates of macro algae, rubble, and sand, with MA being the dominant indicator, though the difference between the substrates is not substantial. At station Waru-waru, the dominant species is *Comaster* (sea lily), which attaches to hard substrates and sandy bottoms. In station Watu Meja, the dominant species are *Comaster*, *Echinaster*, *Stenopus*, and *Phyllidiella*. *Echinaster* is most abundant on sandy and rocky substrates. The habitat of starfish has a wide range, from tropical coral reefs, rocky shores, tidal pools, mud, sand, seagrass beds, and coral reefs to depths of at least 6,000 meters (Rahman et al., 2018). Based on the analysis results, Watu Meja station shows a strong correlation with several species of biota found, with the highest correlation observed with *Echinaster*. A total of 49% of the entire *Echinaster* found came from Watu Meja station (Table 5). In this study, *Echinaster* was found on sandy substrates, with some individuals hiding in the crevices of dead coral covered with algae. Waru-Waru station shows a strong correlation with the biota *Tridacna* or giant clam, which corresponds to the habitat required by clams, which is a depth of less than 5 meters where sunlight can still penetrate the water column. Giant clams need light bottoms that allow sunlight to penetrate for photosynthesis (Liu et al., 2024).

Assemblages dominated by rubble and sand with macroalgal patches mirror nearshore patterns in Gazi Bay (Kenya, Western Indian Ocean), where simplified substrates alter urchin and fish guilds and constrain richness (Ditzel et al., 2022). Experimental hydrodynamic work from the NE Atlantic further shows that local flow modifies near-bottom deposition around coral patches, influencing the effective availability of hard-substrate refugia for echinoderms such as comaster and echinaster (Mienis et al., 2019).

Jetty station and Banyu Tawar station are in the same quadrant and have main characteristic substrates of silt, rock, and DCA. The DCA substrate is the least distinctive, shown by the line closest to the 0 axis. Based on the angles formed, Banyu Tawar station has a strong correlation with biota such as sea cucumbers from the genus *Holothuria* and *Synapta*, and the substrate of DCA. It is known that sea cucumbers feed on organic material and tend to hide under rocks or corals to forage (Setiawan et al., 2019). Based on the data obtained, the dominant biota at Banyu Tawar station is *Drupella*, but in PCA analysis, Banyu Tawar station shows a correlation with sea cucumbers, which is due to the fact that sea cucumbers were only found at this station, unlike the other station.

Comparable habitat-linked peaks of deposit-feeding sea cucumbers occur in Gulf of Mannar and Palk Bay (India) where organic-rich sediments and reef structures co-occur (Asha et al., 2019), and in Duroa Island, Tual City, Maluku (Indonesia), where holothurian diversity and abundance track reef-seagrass mosaics (Kalidi et al., 2023). Feeding studies also show selective assimilation by *Holothuria scabra*, supporting the association with detritus-enriched DCA substrates (Indriana et al., 2018).

Jetty station has a strong correlation with several biota, including *Diadema*, *Tripneustes*, *Phyllidia*, *Cymo*, and *Echinotrix*. These biotas are closely related to substrates such as clay, dead coral, and rocks, as shown by lines forming angles of less than 90°. *Diadema*, *Tripneustes*, and *Echinotrix* have a preference for sandy substrates and low current types. *Cymo* is the biota most strongly correlated with Jetty station, followed by *Diadema*, as indicated by the lines furthest from the 0 axis. *Diadema* is the most abundant species found at Jetty station, which is consistent with the substrate dominated by DCA, sand, silt, and rock. The high density of *Diadema* at Jetty station is related to the habitat suitability for this species. *Diadema* tends to live in groups and hide behind corals or rocks, and most importantly in substrate with greater complexity that provides crevice (Bodmer et al., 2021). Furthermore, the abundance of *Diadema* is influenced by the presence of turf algae, which is a food source for *Diadema* (Manuel et al., 2021). Based on the analysis results, the *Diadema* and macroalgae variables show a negative relationship, as seen from the vectors moving away from each other. This indicates that an increase in the number of *Diadema* may suppress the growth of macroalgae. Although Watu Meja has low hard coral cover (4.10%), this station shows high diversity after Banyu Tawar. This is likely due to the presence of species that are more adaptive to disturbed conditions, as well as low species dominance, allowing more species to live together, increasing species diversity despite limited live coral cover.

At Station Jetty, the dominant species are *Diadema*, *Tripneustes*, *Phyllidia*, *Cymo*, and *Echinotrix*. These species are strongly linked to silt, dead coral, and rock substrates, shows more degraded and disturbed habitat conditions. *Diadema* (sea urchin) is the dominant species at this station, showing a strong relationship with silt and dead coral substrates. The presence of dominant *Diadema* in this station potentially causing low diversity, reducing the opportunity for other species to thrive. But, the presence of *Diadema* has been shown to effectively improve coral reef health by reducing algal cover and cleaning the substrate.

However, the number of individuals needs to be considered. Research suggests that the optimal density for restoration efforts is a minimum of 5 individuals per m² (Manuel et al., 2021). The dominance of *Diadema* at this station is consistent with previous research, where a total of 616 *Diadema* individuals were recorded during four surveys in different seasons from 2021–2022 (Isdianto et al. 2023b), display specific habitat preferences closely tied to their ecological roles as herbivores within coral reefs and rocky substrates. These habitats not only provide food resources but also critical protection from predators by hiding in crevices (Ndobe et al., 2018; Vafidis et al., 2021). Silt substrates and dead coral create less than ideal conditions for many species, and human activities causing increased sediment contribute to substrate degradation and decreased diversity.

Urchin-dominated, low-evenness states under sediment stress are likewise documented on nearshore reefs of Culebra Island, Puerto Rico (Caribbean), where land-use and oceanographic changes reshaped benthic communities (Otaño-Cruz et al., 2019). High *Diadema* abundance aligning with simplified habitats is also reported from the South Aegean Sea (Greece, eastern Mediterranean) (Vafidis et al., 2021), while biomonitoring from İskenderun Bay (Türkiye, eastern Mediterranean) supports Diadema as a coastal stress bioindicator (Uğurlu, 2023). Experimental work in the Caribbean further shows *Diadema antillarum* herbivory can suppress algal cover – consistent with the negative Diadema–macroalgae relationship observed at Jetty (Manuel et al., 2021).

Banyu Tawar station shows dead coral substrate with algae dominating this area. Holothuria (sea cucumber) and Synapta are more frequently found in dead coral with algae substrate, as it feeds on organic material and tends to hide under rocks or corals to feed. Recent studies show that although sea cucumbers may feed on a variety of organic materials like phytoplankton and macroalgae, they exhibit selective feeding behaviors that maximize nutrient uptake from sediments (Indriana et al., 2018; Kalidi et al., 2023). Higher densities of certain sea cucumber species are typically found in seagrass beds and coral reefs – areas rich in organic detritus that benefit these organisms' survival and reproductive success (Asha et al., 2019; Watkins et al., 2023).

These PCA-based associations match global evidence that substrate composition and three-dimensional complexity govern invertebrate community structure across reefs – spanning Kenya (WIO) and Colombia (ETP) to multi-region syntheses of reef invertebrates (Ditzel et al., 2022; Valencia and Giraldo, 2021; Ferrari et al., 2016; Nelson et al., 2016).

CONCLUSIONS

This study highlights the significant influence of substrate type and water quality on the structure and distribution of macroinvertebrate communities in Sempu Strait. Macroinvertebrate density and diversity varied across stations, with the highest abundance observed at Jetty station, dominated by *Diadema* species, reflecting habitat degradation and species dominance. In contrast, stations such as Banyu Tawar and Watu Meja showed higher diversity and evenness, indicating more balanced ecological conditions. principal component analysis showed a significant correlation between substrate type and specific macroinvertebrate species, reaffirming the important role of habitat characteristics in shaping community structure. Overall, these findings underscore the ecological importance of maintaining heterogeneous and stable substrates to support diverse macroinvertebrate assemblages in coral reef ecosystems.

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